NETWORK OPERATIONS

Prime Missions

Voyager at Jupiter

The Voyager Project was the ultimate realization of a much earlier NASA plan to send two robotic spacecraft to visit all of the outer planets of the solar system in the later years of the 1970s. As early as 1969, even as Congress was approving funds for the first exploratory missions to Jupiter (*Pioneers 10*, *11*), NASA was making grand plans for future planetary exploration.

Based on a report from the United States National Academy of Sciences, which found that "exceptionally favorable astronomical opportunities occur in the late 1970s for multiplanet missions," this "mother of all missions" came to be known as the Grand Tour. An additional report, published in 1971, concluded with a specific recommendation "that Mariner-class spacecraft be developed and used in Grand Tour missions for the exploration of the outer planets in a series of four launches in the late 1970s." At least in theory, this unique juxtaposition of the planets would allow a passing spacecraft to use the gravitational pull of one planet to alter its trajectory in such a way as to redirect it toward a flyby of the next planet. The process could be repeated, as required, to make a complete tour of all the outer planets. The technical challenges of such a mission were enormous. Amongst them were precise celestial navigation and deep space communications, both primary functions of the DSN.

In its original form, the NASA plan for the Grand Tour encompassed dual launches to Jupiter, Saturn, and Pluto in 1976 and 1977, and dual launches to Jupiter, Uranus, and Neptune in 1979. A total cost, over the decade, was about $750 million.[3] Later, however, political and budgetary constraints forced NASA to scale back the original plan to two missions to Jupiter and Saturn, with an option for an encounter with Uranus. The total cost of the new missions was to be $250 million, a more acceptable figure in the fiscal climate of the early 1970s.

Congressional approval was soon forthcoming and the official start of the Voyager mission was set for 1 July 1972. NASA designated JPL as the Lead Center and Edward C. Stone, a distinguished expert on magnetophysics from Caltech, as Project Scientist. Because the new mission was based on the proven, JPL-designed Mariner spacecraft, it was initially named MJS, for Mariner Jupiter-Saturn; the name became Voyager in 1977 but most of the early documentation retained the original name. At JPL, Raymond L. Heacock became Project Manager with Richard P. Laeser as his Mission Director, and Esker K. Davis as Tracking and Data Systems Manager, representing the DSN. Although these names changed several times as the mission progressed over the next twenty-five years, the functions always remained the same.

In both concept and execution, the Voyager Project was one of the most ambitious planetary space endeavors ever undertaken. The *Voyager 1* spacecraft was to investigate Jupiter and several of its large satellites, and Saturn and its rings and large satellite, Titan. *Voyager 2* was also to observe Jupiter and Saturn and several of their satellites after which it was to be redirected toward an encounter with Uranus in 1986. After their final encounters, both spacecraft would eventually cross the boundary of the solar system into interstellar space. Each spacecraft would carry instrumentation for conducting eleven scientific investigations in the fields of imaging science, infrared radiation, ultraviolet spectroscopy, photopolarimetry, planetary radio astronomy, magnetic fields, plasma particles, plasma waves, low energy charged particles, cosmic ray particles, and radio science. A new onboard computer system gave the Voyagers greater independence from ground controllers and more versatility in carrying out complex sequences of engineering and scientific operations than on the Mariners earlier.

On each spacecraft, uplink communications with the DSN were provided by two S-band radio receivers while downlink communications used four 25-watt transmitters, two of which operated at S-band and two at X-band. Each spacecraft carried a large, 3.7-meter diameter, high-gain antenna (HGA) in addition to a smaller, low-gain antenna intended for use as backup. Combined with the HGA, the X-band downlink was designed to deliver telemetry data up to 115.4 kilobits per second to the DSN 64-m antennas from the distance of Jupiter.

That was the plan and the basis for the Voyager project requirements for DSN tracking and data acquisition support for the first part of the overall mission—namely the launch phase, cruise phase, and with the Jupiter Encounter.[4] The Network responded to these requirements with the DSN MDS. The MDS and the events associated with the Voyager launch and cruise phases marked the closing stages of the Viking Era. Events associated with the approach of the two Voyager spacecraft to Jupiter, toward the end of 1978, soon showed that transition to the Voyager Era had already begun.

As the year 1979 opened, the space drama unfolding at JPL and featuring *Voyager 1* at Jupiter had begun to attract the attention of space scientists and observers throughout the world. Excerpts from "Voyage to Jupiter"[5] describe the mounting interest. "In mid-January, photos of Jupiter were already being praised for 'showing exceptional details of the planet's multicolored bands of clouds.'" "By early February, Jupiter loomed too large in the narrow-angle camera to be photographed in one piece." Sets of pictures called mosaics were necessary to cover the entire planet body. A spectacular movie covering ten Jupiter days and displaying the swirling vortices of the upper atmosphere would be assembled from thousands of images transmitted from the spacecraft as it approached the planet. These images, transmitted at the rate of about one image per 90 seconds over the X-band downlink at 117 kilobits per second, required 100 hours of continuous DSN coverage to complete.

The *Voyager 1* spacecraft reached its point of closest approach to Jupiter at 4:42 a.m. PST, on 5 March 1979, at a distance of 350,000 km from the planet center and 660 million km from Earth. The governor of California was present at JPL, and a special TV monitor was set up in the White House for President Carter to witness this historic event. A short time before the closest approach to Jupiter, Voyager had begun an intensive sequence of observations of Io. Much of the data, taken during the Canberra pass, was stored on the spacecraft tape recorder and played back later over the Goldstone stations so that it could immediately be transmitted to JPL.

Typical examples of the many images of Jupiter and Io taken by *Voyager 1* are shown in Figures 4-2 and 4-3.

The passage of *Voyager 1* through the Jupiter system is shown in Figure 4-4.

The entire event, from the time it crossed the orbit of Callisto inbound to the time it recrossed it outbound, took only 48 hours. In that short time, equal to two complete passes around the DSN, *Voyager* made observations on a major planet, Jupiter, and five of its satellites—Amalthea, Io, Europa, Ganymede, and Callisto. Never before had a planetary encounter yielded such a wealth of new and unique scientific data. It was truly a major milestone in the history of planetary exploration. In his essay, "Voyager: The Grand Tour of Big Science,"[6] Andrew Butrica noted, "Voyager is planetary exploration on a grand scale." The mission was only just beginning.

As *Voyager 1* receded from Jupiter, it continued to work through the carefully planned post-encounter mission sequences, and accelerated on to a new trajectory that took it to an encounter with Saturn in November 1980.

Voyager 2, four months behind *Voyager 1*, moved into the Jupiter observatory phase and took imaging sequences for another time-lapse movie and activated its UV and fields and particles instruments.

Figure 4-2. *Voyager 1* image of Jupiter, 13 February 1979, at a distance of 20 million kilometers, showing Io (left) and Europa (right) against the Jupiter cloud tops. One of the most spectacular planetary photographs ever taken was obtained on 13 February 1979, as *Voyager 1* continued to approach Jupiter. By that time, at a range of 20 million kilometers, Jupiter loomed too large to fit within a single narrow-angle imaging frame. Passing in front of the planet are the two Galilean satellites. Io, on the left, already shows brightly colored patterns on its surface, while Europa, on the right, is a bland, ice-covered world. The scale of all of these objects is huge by terrestrial standards. Io and Europa are each the size of our Moon, and the Great Red Spot is larger than Earth.

For the next several months, DSN operations activity would be dominated by these two high profile planetary missions. *Voyager 1* post-encounter activities were kept at a low level so that the majority of the support facilities could be devoted to preparation for the *Voyager 2* encounter. The Doppler tracking loop problem in the *Voyager 2* radio receiver complicated each DSN tracking pass by requiring a continuous change in the uplink frequency to compensate for the Doppler shift at the spacecraft. This change could now be predicted and included in the computer driven predicts, but it was also necessary to monitor the spacecraft telemetry to detect any drift in receiver rest frequency and modify these predicts in real time to maintain the spacecraft receiver in lock.

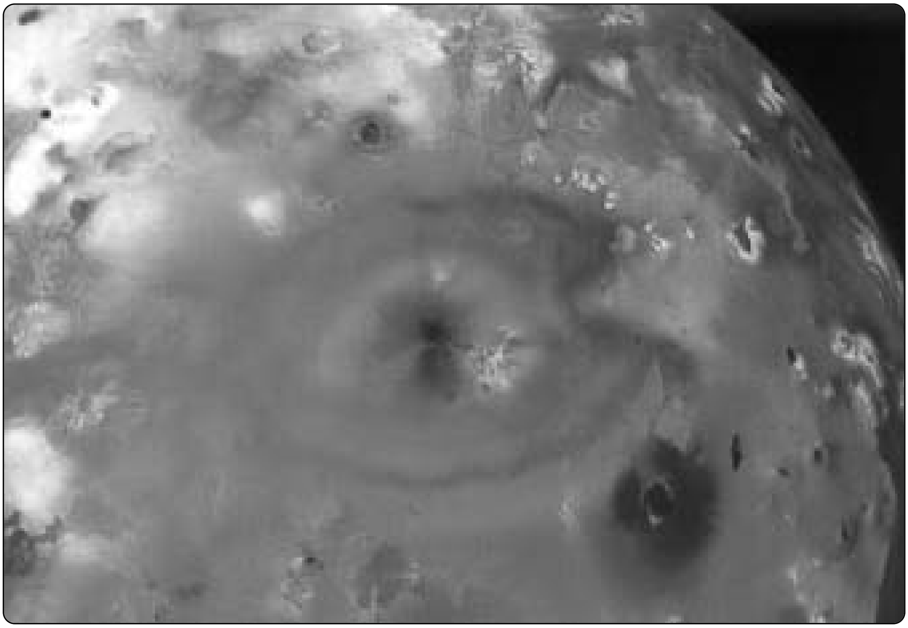

Figure 4-3. *Voyager 1* image of Io, 4 March 1979. Taken at a distance of 400,000 kilometers, the picture shows the giant volcano Pele and strangely colored deposits of surface material.

Despite these difficulties, all transmitted command sequences were accepted by the spacecraft, and uplink and downlink communications were maintained successfully.

As *Voyager 2* closed with Jupiter, the returning images showed clear evidence of the great changes that had taken place in the Jovian atmosphere since the *Voyager 1* encounter in March. In passing through the Jupiter system, *Voyager 2* would be able to fly by the same satellites as *Voyager 1*. It would "see" different faces of Callisto and Ganymede and pass much closer to Europa and Ganymede. Unfortunately, it would pass much further away from the volcanic satellite Io. Although it was not realized at the time, the data from the closer pass to Europa and the further pass from Io would be of great significance when the *Galileo* spacecraft returned to Jupiter seventeen years later. Some of the Voyager sequences were changed as a result of the *Voyager 1* experience, but in general they followed the same pattern.

The Jupiter Encounter occurred at 3:29 p.m. PDT, on 9 July 1979, amid great excitement as new data on the satellites and the planet itself poured in and were released to

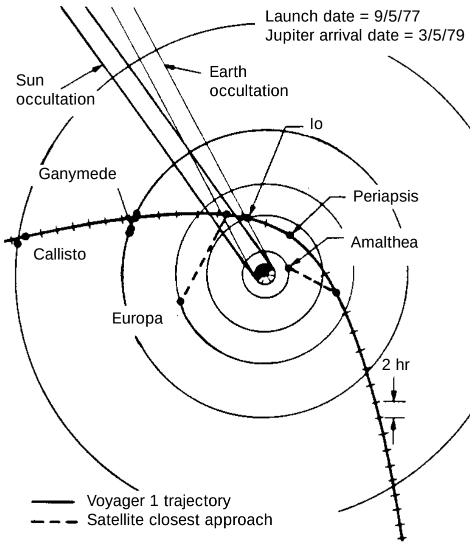

Figure 4-4. *Voyager 1* trajectory through the Jupiter system, 5 March 1979.

the public in the daily press conferences. A new satellite of Jupiter, Andastra, was discovered and a ring quite unlike those of Saturn was observed for the first time. The NASA Associate Administrator for Science, Thomas A. Mutch, was moved to remark that "such events are clearly read into the record. And I submit to you that when the history books are written a hundred years from now . . . the historians are going to cite this particular period of exploration as a turning point in our cultural, our scientific, our intellectual development."[7]

During and after the encounter, there was some concern about the effects of the Jupiter radiation environment on the spacecraft radio receiver. This caused more rapid drift in frequency than expected and actually resulted in loss of the uplink connection with the spacecraft on the day after encounter. By sending repeated commands at various frequencies, the DSN operators were finally able to find a frequency at which the spacecraft receiver would accept the commands, just in time for the commands needed to fire the thrusters for the trajectory correction maneuver that would enable the spacecraft to make the turn for Saturn.

While *Voyager 2* added considerably to the volume of science delivered by *Voyager 1*, it also added to the number of unanswered questions about the "King of Planets." The answers would be a goal for Galileo, the next Jupiter mission, which lay many years in the future. At that time, however, the next exciting goal for both Voyagers lay less than two years away. It was the planet Saturn.

The demand for contiguous support for Voyager and the Pioneer Venus Orbiter in 1979 had forced the DSN to consider economies in the use of tracking station time for pretrack preparation, i.e., the configuration and calibration of the station hardware and software needed for an upcoming spacecraft tracking pass. Prior to this time, the DSN had generally been able to assign a complete station to a flight project in a critical encounter phase, to the exclusion of all other users. In this situation pretrack preparation times of as much as six to eight hours were normally used. Time needed for essential station maintenance consumed additional time. Early in 1979 this was no longer possible because of end to end Voyager and Pioneer view periods of 8 to 10 hours each at the same 64-m sites. To contend with this situation, DSN operations devised a new strategy for pretrack preparation. Pretrack and post-track activities for both spacecraft were drastically shortened and carried out during a single allocated time period.[8] "Quick turnaround" reduced the time allowed between the end of one track and the start of the next to the time required to reposition the antenna and to mount new tapes. In addition, time for routine station maintenance was based on a new formula which ensured an essential, monthly minimum number of hours for each type of antenna.

From this time on, the DSN was under constant pressure to increase the amount of tracking time available for flight project use, often at the expense of reducing or even eliminating, essential maintenance time with consequent risk to station reliability. Over the years, the basic rules devised in 1979 for allocation of pretrack and post-track preparation time have served the DSN well in striking a balance between conflicting demands for maximum antenna tracking time and maximum station reliability.

Voyager at Saturn

In terms of uplink and downlink capability, the requirements of the Voyager missions to Jupiter had been met by the DSN Mark III-77 Data System described in detail in the previous chapter. In fact, several years earlier, the Voyager requirements for telemetry, command, and radiometric data had been one of the principal drivers for that major upgrade to the Network capability and the schedule on which it was carried out (see chapter 2). When completed in April 1978, it provided the Voyager missions with an X-band, high-rate (up to 115 kilobits per second) telemetry downlink at Jupiter range from all three 64-m stations. Radiometric products, in the form of two-way Doppler and ranging data, provided for precise navigation and the S-band, 20-kilowatt, transmitters were more than adequate for command purposes at Jupiter range.

However, to support the Voyager spacecraft at Saturn, double the range of Jupiter, and possibly even Uranus, four times the Jupiter range, substantial enhancements to the Mark III-77 capability, particularly in the detection of weak signals, were required. Because the downlink signal strength diminishes as the square of the spacecraft distance from Earth, the signals reaching the DSN antennas when the spacecraft reached Saturn would be only one-fourth of those received from Jupiter, one-fourth less again when the spacecraft reached Uranus.[9]

These and other issues related to DSN operational support for Voyager were routine topics on the agenda of the weekly Voyager project meetings at JPL. Led by the project manager or the mission director, project meetings were the established JPL forum for negotiation of all requirements and interactions between the DSN and all flight project organizations. Once the actual mission began, the agenda of the regular project meetings was expanded in scope (and duration) to include status and progress reporting, as well as future requirements on the DSN. The meetings comprised representatives from each of the institutional organizations involved with that particular flight project, of which the DSN was one. Marvin R. Traxler represented the DSN to the Voyager project. The DSN appointed similar representatives to each of the flight projects to speak on DSN matters.

It should be pointed out that negotiations between the flight projects and the DSN, which involved the design and implementation of new DSN capabilities, were completed as much as five years prior to the "time of need," due to the long lead time required for the DSN approval, funding, contractual, implementation, testing, and operational training processes. In some cases, even five years proved to be insufficient time. That is the reason for the long planning periods represented by future missions in the charts of the DSN mission sets for the various eras (see Figure 4-1 for the Voyager Era). A formal set of top level documentation conveyed the project "requirements" and the DSN "commitments" to the two Program Offices at NASA Headquarters, the Office of Space Science (OSS) and Tracking and Data Acquisition (OTDA), for formal, top-level approval. Lower tier documents within the project and the DSN disseminated the necessary technical and operational detail to the implementing organizations. These steps infrequently occurred in serial fashion. Rather, driven by the always-pressing flight project schedules, work proceeded on the assumption that the necessary formalities would be eventually completed. Interactions between the flight projects and the DSN were iterative in nature; as space communications technology advanced, the technical requirements of deep space missions advanced to justify the implementation of the new technology in the Network, and vice versa.

Such was the case for Voyager. Even as the two Voyager spacecraft left their launch pads bound for Jupiter in 1977, engineers in Robertson Stevens's Telecommunications Division at JPL had turned their attention and considerable talents to the enhancements that would be needed for the existing Network capabilities to support the Voyager spacecraft, if and when they reached Saturn, Uranus, or even Neptune. Of course these enhancements would benefit all deep space missions; NASA insisted that they be multimission in nature, and so they were, although they were generally attributed to the first mission to make use of them.

Ultimately, the flight project requirements that had been approved for implementation in the Network were published in the form of a plan, jointly signed by project and DSN representatives. The referenced DSN Preparation Plan for Voyager is typical of those prepared for all flight projects which used the Network at various times.[10]

The final plan to meet the Voyager project requirements for DSN support of the two Saturn encounters included the addition of major new or improved capabilities, to the existing Network, in the following technical areas:

1. S-band and X-band antennas: Capability to receive both S-band and X-band downlinks at three 34-m stations and three 64-m stations. All 64-m antennas were optimized with X-band, low-noise masers for improved downlink performance, and with special microwave feeds for radio science experiments during encounter.

2. Downlink signal enhancement: Two-station arraying at each Complex using the 34-m and 64-m antennas and the Real-Time Combiners to improve the signal margin by about 1.0 dB (approximately 25 percent) compared to the 64-m antenna alone. This would allow the downlink telemetry rate to run as high as 44.8 kilobits per second.

3. Precision navigation: Up to six different kinds of radiometric data to enhance spacecraft navigation and radio science experiments by allowing for the removal of charged particle effects in the interplanetary media. These data types consisted of various combinations of S-band and X-band Doppler and ranging data. Besides basic improvements in the accuracy of the ranging system, the DSN Tracking System also included automatic uplink frequency tuning to compensate for the failed frequency tracking loop in the *Voyager 2* transponder.

4. Radio science augmentation: New precision powered monitors, spectrum signal indicators, open-loop receivers and multiple-channel, wideband, digital recorders together with appropriate software were installed at DSS 63 Madrid, the prime radio science station designated by Voyager for covering the occultation and Saturn rings experiments during the *Voyager 1* encounter. Later, some of this equipment was moved to the Canberra site and installed at DSS 43 to cover the *Voyager 2* encounter. This equipment measured changes to the inherent radio frequency characteristics (polarization, phase delay, spectral spreading, scintillation, etc.) of the Voyager radio signal as it grazed the Saturn atmosphere or passed through the rings. Later analysis of wideband recordings of these data provided significant new scientific data on the composition of the atmosphere and the structure of the rings.

The manner in which this work, together with other project-related activity, was carried out during the Voyager Era is described in a later section on Network engineering and implementation.

Following their highly successful encounters with Jupiter in 1979, both Voyager spacecraft commenced the Jupiter-Saturn cruise phase of the mission. The Saturn trajectories had been established as the spacecraft passed Jupiter and, in the months that followed, both spacecraft carried out routine engineering, science, test, and calibration activities. While these routine activities were in progress, the spacecraft carried out a number of special activities.

In February 1980, a delicate cruise science maneuver, which involved turning the spacecraft away from the Earth pointing direction, was performed. The maneuver went well and the spacecraft reacquired the uplink after the antenna came back to Earth point. The scan platform was calibrated in March, and the Canopus star tracker sensitivity was checked in April. Numerous navigation cycles were carried out to refine the radiometric data used for spacecraft orbit determination. A navigation cycle consists of one continuous uninterrupted pass around the Network. Radiometric data, consisting of Doppler, ranging, and a new data type called Delta Differential One-way Ranging (Delta-DOR), are generated by each of the participating stations in turn, as the spacecraft passes through each longitude.

While the real-time operations elements of the Network were supporting all of these Voyager related activities, other parts of the DSN operations organization were also busy, preparing for the upcoming Saturn Encounter.

In March 1980, operations and engineering representatives from the stations in Spain and Australia arrived at Goldstone for training in the installation and operation of a new device called a Real-Time Combiner (RTC). The RTC enabled the signals from two or more separate antennas to be combined electronically to produce a single output of considerably greater strength than either of the input signals alone. When used in this manner, the antennas were said to be arrayed. The RTC had been used earlier in a two-station array at Goldstone during the *Voyager 2* Jupiter Encounter, with encouraging results. The X-band downlink signals from the DSS 14, 64-m antenna had been combined with the signals from the new DSS 12, 34-m antenna to give a telemetry signal gain of 1.1 dB relative to the 64-m antenna alone. This result, obtained under real-time operational conditions, agreed well with the theoretical, predicted value of 1.1 (±0.2) dB. There was great interest in adding a similar capability at the two other 64-m sites where the 26-m to 34-m antenna upgrades were just being completed. After completing the classroom courses and receiving operations experience, the trainees would return to their home sites to replicate the Goldstone installations.

The overseas sites, Deep Space Station 42 (DSS 42) in Australia and DSS 61 in Spain, were being requalified for operational support following the upgrade of their antennas from 26-meter to 34-meter diameter. In May, DSS 14 (Goldstone) and DSS 62 (Spain) were returned to operational status after requalification following antenna downtime for replacement of the subreflector at DSS 14 and repair of the antenna drive gear boxes at DSS 62.

All of the DSN upgrades and modifications to hardware planned for the Voyager Saturn Encounter had been completed and declared operational by mid-1980. In addition, seven new software packages needed for the antenna, communications, command, radiometric, meteorological, occultation, and planetary ranging systems were installed throughout the Network and certified for operational use. The DSN was ready for the first Voyager Saturn Encounter.[11]

Voyager 1 began its concentrated observations of Saturn on 22 August 1980, just 82 days before its closest approach to the ringed planet. At that time, the spacecraft was travelling with a heliocentric velocity of 45,675 miles per hour, at a distance of 67.6 million miles from the planet. The radio signals from the DSN antennas were taking 80 minutes to travel the distance of 901 million miles from Earth to the *Voyager* spacecraft.[12]

The DSN began a series of navigation cycles around the Network to provide precise orbit determination data on which the spacecraft Navigation Team would base the parameters for the final trajectory correction maneuver to fly close by, but not impact, Titan.

In addition, the unique geometry of the Saturn Encounter, zero declination, required highly accurate ranging measurements from two stations simultaneously to provide radiometric data from which the declination of the spacecraft orbit could be determined.

Earlier, the spacecraft had experienced some minor hardware problems in the Canopus star tracker and the scan platform supporting the cameras, but neither was expected to pose a serious problem to the planned Saturn Encounter activities.

The Canopus star tracker helped stabilize the spacecraft and keep it properly oriented by tracking Earth, the Sun, and a reference star, normally Canopus. A backup star tracker was available for use if needed. The scan platform supported the imaging cameras and other science instruments, and under certain conditions of operation had shown a slow drift which could be compensated for, if necessary.

By making use of the 28 percent gain in downlink signal power that would result from using the DSN 34-m and 64-m antennas in the arrayed mode at all three complexes, the Voyager mission controllers planned to run the spacecraft downlink at a telemetry data rate of 44.8 kilobits per second. Without arraying, the maximum data rate possible from Saturn would have been only 29.9 kilobits per second. By contrast, the data rate at the Jupiter Encounter had been 115.2 kilobits per second due to the much shorter spacecraft to Earth range of 413 million miles.

The onboard planetary radio astronomy experiment had been used to determine the rotation rate of Saturn with greater precision than was possible with Earth-based measurements, and cyclical bursts of nonthermal radio noise had been detected. Daily scans of the planet by the ultraviolet spectroscopy instrument were searching for hydrogen sources, and fields and particles instruments were constantly monitoring the interplanetary medium near Saturn. Hundreds of photographs were being taken by the imaging system to compile a full color "time-lapse" movie as the Voyager spacecraft zoomed in on the planet. One of the spectacular pictures from this period is shown in Figure 4-5. At the time this picture was taken, *Voyager 1* was 80 days from Saturn Encounter at a distance of 66 million miles. In addition to the planet itself, three satellites could be seen, and the inner and outer rings, separated by Cassini's division, were clearly visible. The imaging data was transmitted from the spacecraft over DSS 43 at a data rate of 44.8 kilobits per second.

Before the spacecraft reached Saturn, it passed behind the Sun as viewed from Earth. During this period of solar conjunction, from 3 September through 6 October, the angle defined by the Sun, Earth, and Voyager became 15 degrees or less, and the radio noise emitted by the Sun gradually degraded the radio downlink to the DSN tracking sta-

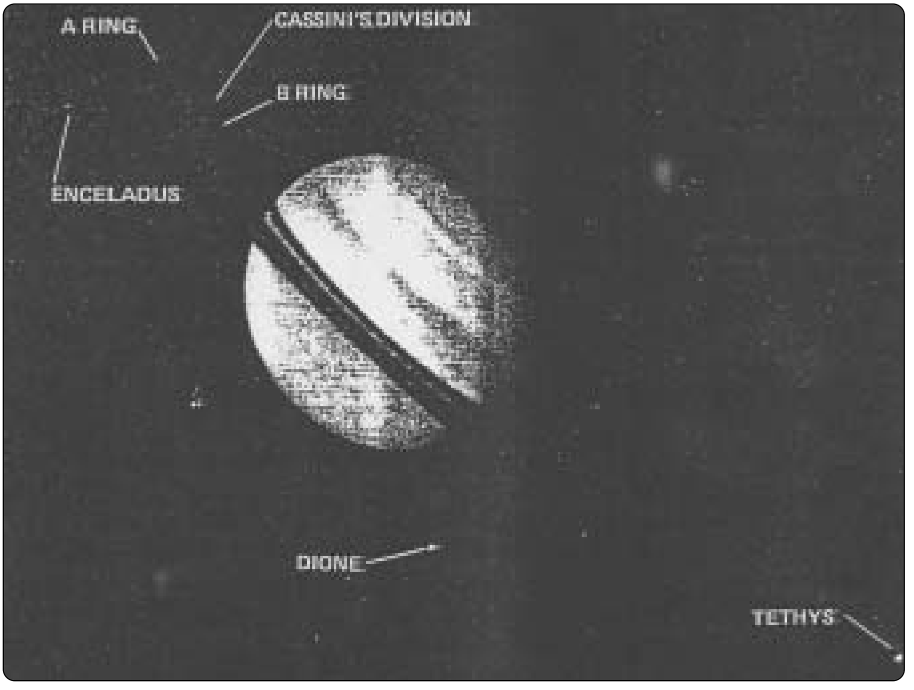

Figure 4-5. *Voyager 1* image of Saturn and its rings, August 1980. Taken on 24 August 1980, 80 days before closest approach at a distance of 66 million miles, this image shows the Saturnian satellites Enceladus, Dione, and Tethys.

tions. However, these conditions provided a unique opportunity for the radio astronomy observations of the Sun and heliosphere as the radio signals from the spacecraft passed through the solar corona. At each of the Deep Space Communications Complexes, the radio science equipment had been upgraded with new and improved hardware and software in anticipation of these imminent events.

Following the solar conjunction period, the uplink and downlink performance returned to normal as the spacecraft continued to rapidly approach the planet.

By 24 October, 19 days before encounter, the field of view of the narrow angle camera could no longer cover Saturn in one frame. It took four pictures to image the entire planet. Ten days later, the Saturn image was larger still and more mosaic pictures were needed to cover it. Attention was then focussed on more detailed examination of the

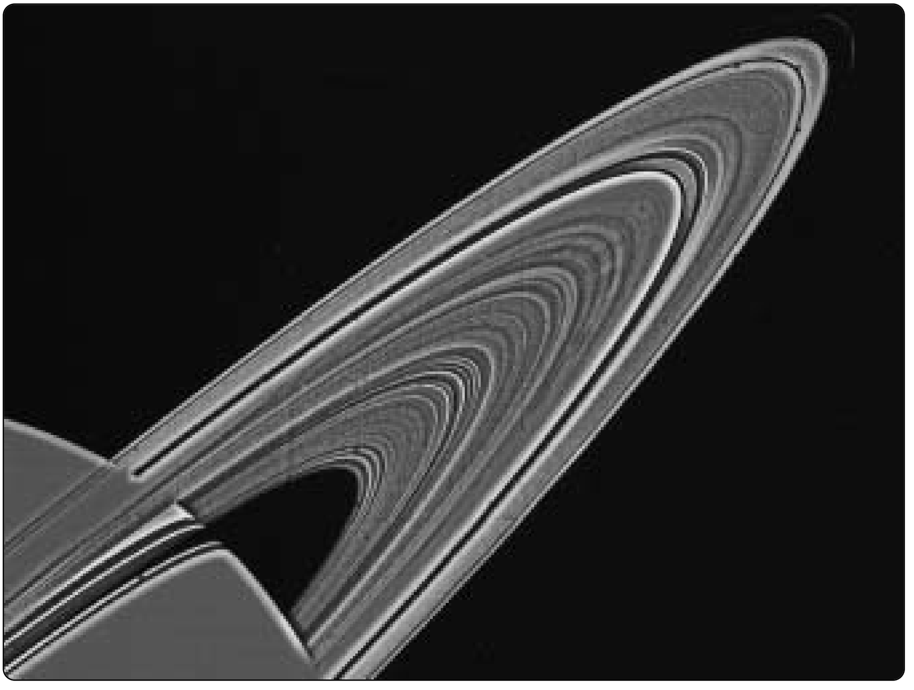

Figure 4-6. *Voyager 1* image of Saturn and its rings, November 1980, shows approximately 95 individual concentric rings.

planetary features. The extraordinarily complex structure of the Saturn ring system was shown in a mosaic of two images taken on 6 November from a distance of 4.9 million miles. (See Figure 4-6.)

On 11 November 1980, twenty-six hours before reaching the point of closest approach to the planet, the spacecraft began executing the encounter sequences which had been preprogrammed into its onboard computers months earlier. Downlink telemetry rates varied between 19.2 kbps and 44.8 kbps as the spacecraft automatically switched through various formats to return imaging, general science, and playback data in rapid succession. Taking high-resolution pictures as it went, the spacecraft would first pass close (7,000 km) by the haze-covered satellite Titan before dipping below the ring plane as it accelerated toward the point of closest approach. Eighteen hours later, on 12 November 1980, *Voyager 1* reached its closest point to Saturn, 184,000 km from the center and 124,000 km above the cloudtops of the shadowed southern hemisphere.

Some 100 minutes after closest approach, the spacecraft passed behind Saturn and remained obscured from Earth for 90 minutes. During this time, and at entrance and exit from occultation, DSS 43 and DSS 63 carried out valuable radio science measurements related to an understanding of the structure and composition of the Saturn atmosphere and ionosphere. At this point the radio signal from the spacecraft was taking four and one-half hours to reach the Earth-bound antennas of the DSN.

Voyager 1 continued to observe the planet and its satellites through December 15, at which time the Saturn post-encounter phase ended and a new phase of scientific data collection began. For as long as the DSN could maintain an uplink and a downlink with the spacecraft it would continue to observe the planetary medium, participating in celestial mechanics and solar experiments with other spacecraft travelling through the solar system. It was now on a solar system escape trajectory that would take it out of the plane of the ecliptic, the plane of Earth's orbit around the Sun. Someday, *Voyager 1* and other planetary spacecraft will reach the heliopause, the outer edge of the solar system. The DSN will continue to track these spacecraft, each going in a different direction to try to determine the size of this invisible region of our solar system. It was expected that *Voyager 1* would cross the heliopause in about ten years, 1990, at a distance of 40 AU.[13]

Voyager 1 had completed its primary mission of planetary exploration. There were no other planets along its new path nor could its path be changed even if there were. Eventually, it would exit the solar system altogether, climb above the ecliptic towards the constellation Ophiacus, and chase but never catch it for all time.

The attention of the Voyager project returned to *Voyager 2*, now seven months away from its encounter with Saturn in August 1981.

During the encounter phase of the *Voyager 1* mission, the mission operations activity on *Voyager 2* had been relatively quiet, with most of the DSN tracking support being provided by the 26-m network, while *Voyager 1* dominated the 64-m and 34-m networks. Beginning in February 1981, however, the pace on *Voyager 2* picked up as the DSN raced to complete several major new capabilities needed to support the *Voyager 2* Saturn Encounter.

The equipment used for the *Voyager 1* radio science observations had to be moved from DSS 63 in Spain to DSS 43 in Australia, the prime viewing site for *Voyager 2* solar conjunction. This equipment, which included the four-channel narrow band and wide band receivers and associated digital recording assemblies, had to be integrated with new software in the Occultation Data Assembly and tested while operational procedures were developed and crew training progressed in parallel.

The receiver problem on *Voyager 2*, described earlier, had now become a “fact of life” with which the DSN had to deal. To this end, the DSN had developed new software to automatically control the Digitally Controlled Oscillator (DCO) which drives the frequency of the uplink transmitter. The DCO would be programmed to compensate for the inability of the *Voyager 2* spacecraft receiver to acquire and track the uplink frequency transmitted by the DSSs, because of its failed tracking loop. It would reside in the Metric Data Assembly (MDA).

There was, however, a complication introduced by spacecraft internal temperature change. It had been determined that various spacecraft activities would cause compartment temperature changes, which would in turn cause the center frequency of the spacecraft receiver to drift in an unpredictable manner. This would make it very difficult or impossible for the DSN to set the transmitter frequency to the exact Best Lock Frequency (BLF) needed to track the spacecraft receiver. To provide background data on the frequency offset and drift caused by spacecraft temperature variations, the DSN had been supporting a special tracking procedure known as “adaptive tracking.” In an “adaptive tracking” sequence, the 34-/64-m station carries out a series of uplink frequency ramps estimated to pass through the BLF. By observing the spacecraft receiver reaction to the uplink frequency ramps, a real-time determination of the correct value of the BLF and its drift can be made. These data can then be used to program the DCO to keep the uplink frequency centered in the slowly drifting receiver pass band.

The DSN would need to use “adaptive tracking” during the *Voyager 2* Near Encounter period to ensure rapid and reliable acquisition of the spacecraft receiver for uplink command purposes. The key to this new capability was the new MDA software which drove the DCO.

This software was installed at all sites by midyear. After the operations crews were trained in its use, it was verified for encounter operations by conducting demonstration tracks with the live spacecraft.

Early in 1981, the DSS 12 antenna, upgraded to 34-m in time for the Jupiter Encounter, was decommitted from support operations for six weeks for further upgrade work to improve its radio efficiency. The two outer rows of antenna surface panels were replaced and reset, and the subreflector surface was replaced with one designed for better illumination of the primary antenna. The controller for the subreflector was also upgraded.

The net result of this work was an improvement of 0.7 dB in antenna gain, demonstrated on the first operational pass when the antenna returned to service in April. The DSS 12/14 array would also benefit during encounter operations.

On 5 June 1981, the observation phase of the *Voyager* 2 Saturn Encounter began. The first activity was the movie sequence, which started over the Madrid Complex with Deep Space Stations 61 and 63 (DSS 61 and DSS 63) tracking the spacecraft, and was concluded on 7 June over the Canberra Complex with tracking support by DSS 42 and DSS 43. During the movie phase, the arrayed 34-/64-m configuration was used at all complexes to enhance the received imaging telemetry data. The performance of the arrayed stations was well within the predicted tolerances and resulted in excellent picture data quality.

While the spacecraft team conducted a sequence of scientific observations somewhat similar to those conducted by *Voyager 1*, the DSN completed the remaining hardware and software items needed for encounter, and enhanced the proficiency of the DSS crews with Operational Verification Tests.

Beginning with the passes over DSS 61 and DSS 63 on 13 August, and continuing around the Network for several days, high rate imaging data were obtained by the DSN. The 34-m and 64-m stations were arrayed for this support and the real-time data were received at 44.8 kbps with playback data at 29.8 kbps. These images, which were taken under better lighting conditions and at a better approach angle than had been possible on *Voyager 1*, were later used by the project to compile a Saturn rings movie.

A final pre-encounter trajectory correction maneuver on 18 August was supported over DSS 12 and DSS 14. During the maneuver sequence, the spacecraft antenna was placed off Earth point for over an hour resulting in loss of the downlink for that time. DSS 14 reacquired at the proper time and the telemetry data indicated that the trajectory correction had been performed correctly.

In preparation for the extensive radio science activities which would occur over DSS 43 during this encounter, a final radio science Operational Readiness Test was conducted with the Canberra Complex on 19 and 20 August. All of the encounter equipment was operational, and the actual operational sequence was used for the test. With the successful completion of this test, the DSN was declared ready to support the second Voyager encounter of Saturn.[14]

The Near Encounter Mission phase started on 25 August 1981. Recording of celestial mechanics data in the form of closed-loop Doppler and ranging data had begun earlier and was continued through the encounter period. High-rate imaging data of the closest approach sequences from the narrow-angle camera was obtained at 44.8 kbps in the arrayed mode. Image reception in the arrayed configuration was excellent and no images were lost due to DSN operations. With most of its Saturn observations completed, *Voyager 2* passed within 63,000 miles (101,000 km) of the Saturn cloudtops, at 9.50 p.m. (Earth Received Time), 25 August 1981. Still to come were observations of the dark side of the planet and southern hemisphere, the underside of the rings, and several satellites.

Shortly after 10 p.m. PDT, the imaging sequence ended and the spacecraft began to disappear behind the disk of Saturn. For the next 90 minutes, it would remain occulted by the planet. As it entered occultation, and again as it exited, the DSN radio science System at DSS 43 recorded open-loop and closed-loop receiver data. The data would yield information regarding the Saturn atmosphere and ionosphere and the microwave-scattering properties of the rings.

When the spacecraft exited occultation and the DSS 43 downlink was reestablished, telemetry data indicated that the scan platform had not carried out its programmed pointing sequences while it was behind the planet. Only black sky image frames were being received. Playback of the tape recorder data from the spacecraft indicated that the scan platform had functioned properly while the spacecraft was occulted and the fault had occurred just prior to egress. Investigation of the problem by the project resulted in restoration of the scan platform capability some days later and the Saturn imaging sequences resumed. Throughout all of this action, the DSN continued to provide Network support and accommodate numerous schedule and sequence changes as the situation required.

A trajectory correction maneuver on 29 September refined the *Voyager 2* flight path to Uranus with a swing-by assist toward Neptune.

Preliminary science results from *Voyager 2* revealed that subtle changes had taken place in the Saturn atmosphere since the *Voyager 1* visit nine months earlier. *Voyager 2* saw more detail in the atmosphere and much more detail in the rings, which could be numbered in the thousands. *Voyager 2*'s trajectory took it on a wide arc through Saturn's magnetic field, exploring different regions and adding to the data obtained by *Pioneer 11* and *Voyager 1*. On its passage through the Saturn system, *Voyager 2* passed closer to some of the satellites, further away from others, than did *Voyager 1*, and it returned a magnificent set of images of the planet and all its major satellites.

DSN support of the *Voyager 2* Near Encounter activities at Saturn was accomplished without any significant problems. Radio science played a major part of the encounter operations at DSS 43. During the closest approach period, DSS 43 generated 10 medium-band and 40 wide-band Digital Original Data Records (DODRs) for radio science. These were used to produce 484 radio science intermediate data records (IDRs). All DSN Near Encounter operations were conducted in the arrayed mode. The quality of telemetry imaging data was excellent and no images were lost.

Even with the scan platform problem, it was considered that the Voyager Saturn mission objectives had been met.

The DSN contributed to this success in two most significant ways. First, the successful operational use of "adaptive tracking" mode enabled the DSN to accommodate the uplink problems created by the failed spacecraft receiver tracking circuit, and second, the excellent performance of the Network in using the "arrayed" configuration to enhance the downlink performance to the point where 44.8 kbps real-time telemetry data at Saturn range became a reality for the first time ever.

By the end of August 1981, *Voyager 2* had completed nearly half of its three-billion-mile journey to Uranus, measured from the launch in August 1977 to Uranus Encounter in January 1986. Then four years old, the spacecraft was in good condition except for the radio receiver problem discussed above and some difficulty with the scan platform pointing sequences which stuck, shortly after closest approach to Saturn on 25 August. Since then, the anomaly had been thoroughly analyzed and understood, and the scan platform had been maneuvered successfully several times. Prospects for a successful Uranus Encounter appeared to be good.

Nevertheless, at the final press conference for the Saturn 2 Encounter, several of the speakers, including Ed Stone, the Imaging Team Leader, and Bruce Murray, the JPL Director, reminded those present of the long hiatus in deep space missions that lay ahead. It would be five years before the DSN would see the launch of another deep space mission, and that would be Galileo—or so they thought.

Venus Balloon/Pathfinder

In the period between 1983 and 1985, as international relations between the Soviet Union and the United States began to improve, the first signs of scientific collaboration in space-related endeavors appeared in the form of a cooperative project involving scientists of the Soviet, French, and American space agencies. It would be called called Venus Balloon/Pathfinder. As Bruce Murray observed, "This technical partnership between the United States, Europe, and Russia came about despite the absence of any formal relations between NASA and the Soviet Union. The original U.S.-USSR bilateral space agreements of 1972 (which facilitated, among other endeavors, the Apollo-Soyuz handshake in space in 1975) expired in 1982. Renewal became a casualty of U.S. hostility to the USSR, triggered by the Soviets' suppression of the Solidarity movement in Poland and their invasion of Afghanistan."[15]

On 11 and 15 June 1985, the Soviet *VEGA 1* and *VEGA 2* spacecraft released two instrumented balloons into the atmosphere of Venus. The VEGA spacecraft continued past the planet on their way to a rendezvous with Comet Halley in March 1986. Drifting with the Venus winds at an altitude of about 54 km, the balloons travelled one-third of the way around the planet during their 46-hour lifetimes. Sensors carried by the balloons made periodic measurements of atmospheric pressure and temperature, vertical wind velocity, cloud particle density, ambient light level, and frequency of lightning. The data were transmitted to Earth and received at the DSN 64-m antennas and at several large antennas in the USSR. Approximately 95 percent of the telemetry data were successfully decoded at the DSN complexes and in the Soviet Union, and were provided to the international science community for analysis.[16] These data would supplement current knowledge of the Venus atmosphere obtained by earlier Soviet Venera spacecraft and the NASA Pioneer Venus Probes.

Ground-based tracking support for the Venus balloon experiment involved an international network of about a dozen radio astronomy antennas organized by the French space agency, CNES, a more limited internal Soviet Network and the three 64-m antennas of NASA's Deep Space Network.[17]

Consequent upon the negotiation of appropriate diplomatic and technical agreements in Moscow, Paris, and Washington, the DSN managers determined the trajectories of both the *VEGA 1* and *2* bus spacecraft during the Venus flyby phase to recover telemetry from the balloon signal and, as part of the international network, to acquire VLBI data from each balloon/bus pair while the two were within the same antenna beamwidth.

To meet these commitments, the DSN would employ, as far as possible, existing capabilities normally used for planetary spacecraft navigation, radio science, and radio astronomy. However, there were some special requirements connected with the Soviet spacecraft's L-band downlink and telemetry system.

To deal with the downlink, JPL engineers designed, built, and installed L-band feedhorns and low noise amplifiers at all three 64-m antennas. An L-band to S-band frequency-up converter provided an S-band signal spectrum to the radio science and receiver-exciter subsystems for subsequent extraction and recording of telemetry spectra, one-way Doppler and the essential DDOR and very long baseline interferometry (VLBI) data. The telemetry system was not so straightforward. The peculiarities of the Venus Balloon telemetry system required the development of special software to extract the telemetry data burst from an open-loop recording of the L-band spectrum transmitted by the balloon. Owing to the somewhat unusual nature of this mission, the normal JPL software development resources were not available to the DSN which had, therefore, to seek help elsewhere. The necessary help and expertise needed to produce the software came from Spain in the form of a software development team led by Jose M. Urech and the engineering staff of the Madrid complex.[18]

Jose M. Urech was director of the Madrid Deep Space Communications Complex at Robledo from 1981 until his retirement in 1999. Prior to becoming Director, he had served for fifteen years as servo engineer and station analyst for NASA's 26-m station at Cerebros near Robledo. At retirement, he had been associated with NASA tracking stations as a foreign national for thirty-three years.

Dr. Urech had roots in Madrid, Spain, and was educated in both Spain and France prior to earning a doctorate in engineering from the Polytechnic University of Spain in 1969.

Quiet-spoken, courteous, and low-key in manner, with a partiality for good food and wine, he engendered confidence in all who dealt with him, at whatever level, in NASA business. His social graces, technical ability, and leadership skills were of great help in integrating his team of Spanish engineers into the American-oriented methodology of the space program, and in minimizing the inevitable effect of cultural differences in resolving issues that occasionally arose between the two.

In addition to carrying out his management responsibilities, Jose Urech made time to pursue his technical interests. In 1969 and 1970, he first developed and demonstrated the concept of combining the output of two antennas to improve telemetry reception. This experiment, the first of its kind in the DSN, arrayed two antennas, 20 km apart, to enhance the downlink signal from *Pioneer 8*. In 1985, Jose Urech led a team of engineers from the Madrid station in the development of the special software needed to process the telemetry signals from the Venus Balloon mission. He also contributed to that mission by coordinating the various technical efforts of participants from JPL/NASA, CNES (France), and IKI (USSR).

Throughout his career, Urech was highly regarded by JPL as a valuable consultant and additional resource that could be, and frequently was, called upon to address technical questions related to the performance and productivity of the tracking stations.

He retired from NASA/INTA in 1999 to pursue his interests in active outdoor activities, music, and science, and to assist his wife with her business ventures.

The success of the Venus Balloon experiment depended on two new, very precise orbit determination techniques—Delta differential one-way ranging (DDOR), which was used for the Voyager planetary spacecraft navigation by the DSN, and the VLBI, which was used by radio astronomers for determining the position of extra-galactic radio sources.

The DSN would use DDOR and one-way Doppler techniques to determine the main spacecraft (bus) trajectory, for a two-week period, around the time of Venus flyby. Balloon position and velocity would be obtained from VLBI measurements between the main spacecraft and the balloon, taken by an international network of ground-based radio astronomy antennas, which included the three 64-m antennas of the DSN, over a period of approximately two days near each Venus Encounter, when both bus and balloon were in the same DSN antenna beamwidth.

The DDOR navigation technique employed by the DSN for very precise determination of spacecraft orbits required a measurement on a nearby extra-galactic radio source (EGRS). To find EGRS suitable for VEGA orbit determination, the DSN first had to make measurements of the L-band correlated flux density of 44 potential EGRS taken from the existing JPL radio source catalog of 2.3 GHz and 8.4 GHz sources.[19]

During the actual encounter period, the DSN performance in all three areas of support was satisfactory. Balloon telemetry data obtained by the DSN were provided to the science teams on computer-compatible magnetic tape in the form of original recorded spectra and in the form of demodulated and decoded data streams. Most of the decoded telemetry data was provided from MDSCC where Spanish engineers succeeded in adaptively adjusting their data processing software to compensate for the totally unexpected wind conditions on Venus that created Doppler rates up to fifty times greater than the predicted values on which the software designs were based.

Only seven of the ninety-two balloon telemetry transmissions were missed, mainly due to downlink signal variations caused by the balloon itself.[20]

During the fifteen-day period of Venus Encounter observations, the DSN succeeded in obtaining good DDOR data on 85 percent of the attempts. These data formed the basis for the VEGA flyby orbit determination. The DSN also obtained good VLBI data on sixty-seven of the sixty-nine balloon transmissions. These data, in conjunction with the VEGA orbit data, were used to estimate balloon position and velocity.

The end of the Venus Balloon experiment did not, however, spell the end of DSN involvement with the two VEGA spacecraft. Nine months later, in early 1986, the DSN would again be providing DDOR data from the VEGA spacecraft in support of Pathfinder operations for the Giotto mission to Comet Halley.

DSN support for these missions took place as the DSN moved into the Galileo Era described in the next chapter.

Voyager at Uranus

The Downlink Problem

As the excitement associated with the successful Saturn encounters in 1980 and 1981 subsided and the two Voyager spacecraft began to move along their new trajectories, *Voyager 1* toward the edge of the solar system and *Voyager 2* toward Uranus, the Voyager Project and the DSN began negotiations for even more enhanced tracking and data acquisition support than that provided for Saturn. At a distance of 20 AU from Earth, double the range of Saturn, with the downlink signal correspondingly reduced to 25 percent of its strength, the Voyager requirements for Uranus posed a further challenge to the ingenuity, innovation, and expertise of JPL's Telecommunication Division, which provided engineering support to the DSN. Basically, the problem was that of compensating for the loss of downlink due to increased spacecraft range (at Uranus) with increased signal gathering capability on the ground.

In the early 1980s, the DSN had adequate technical capability to support the planetary missions then in the mission set, at distances of 5 to 10 times the Earth-Sun distance, 5 to 10 Astronomical Units (AU). It was not until the successful Saturn Encounter in

August 1981 that a Uranus Encounter at 20 AU in 1986 became a real possibility. The DSN antennas did not then have the additional 4 to 6 dB of downlink capability that would be required to support the desired imaging data rate from *Voyager 2* at the distance of Uranus.[21]

The NASA planetary program was entering the hiatus period of the 1980s and, other than *Voyager 2* at Uranus and possibly Neptune, there were no future missions in view that would justify additional, large, new antennas. However, earlier DSN studies had drawn attention to the significant improvement in downlink performance that could be obtained from an array of existing antennas.[22] Furthermore, it was (theoretically) possible, by the use of data compression techniques in the spacecraft, to increase the efficiency of the telemetry data stream itself. By combining the improvements derived from DSN arraying with the improvements resulting from spacecraft data compression, the downlink capability required to obtain the desired science data return at Uranus could be realized.

Voyager 2 at Uranus in 1986 could not be regarded as merely a five-year extension of the 1981 Voyager Jupiter-Saturn mission, for it was indeed a new mission from a DSN point of view. It had been renamed the Voyager Uranus Interstellar Mission.

To this end, a comprehensive study of DSN options for employing arraying techniques to enhance DSN downlink performance for Voyager encounters of Uranus and possibly Neptune was undertaken in 1982. The study was not limited to DSN antennas and therefore included a survey of all known large antenna facilities, including those of Australia, England, Germany, Japan, Italy, and Russia. The “Interagency Array Study” Team was led by J. W. Layland and published its recommendations in April 1983.[23]

In considering arrangements for interagency arraying, the study recommended that permanent ties should be sought with other space agencies such as Japan’s Institute for Space and Aeronautical Science (ISAS), but that for shorter term goals, such as support of Voyager at Uranus, a radio astronomy observatory seemed more appropriate. In this context, the array of the Canberra Deep Space Communications Complex (CDSCC) with the 64-m antenna of the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) radio astronomy observatory at Parkes, New South Wales, was recommended as most viable DSN configuration for support of the Voyager at Uranus. A photograph of the 64-m antenna of the CSIRO radio astronomy observatory at Parkes, New South Wales, Australia, is shown in Figure 4-7.

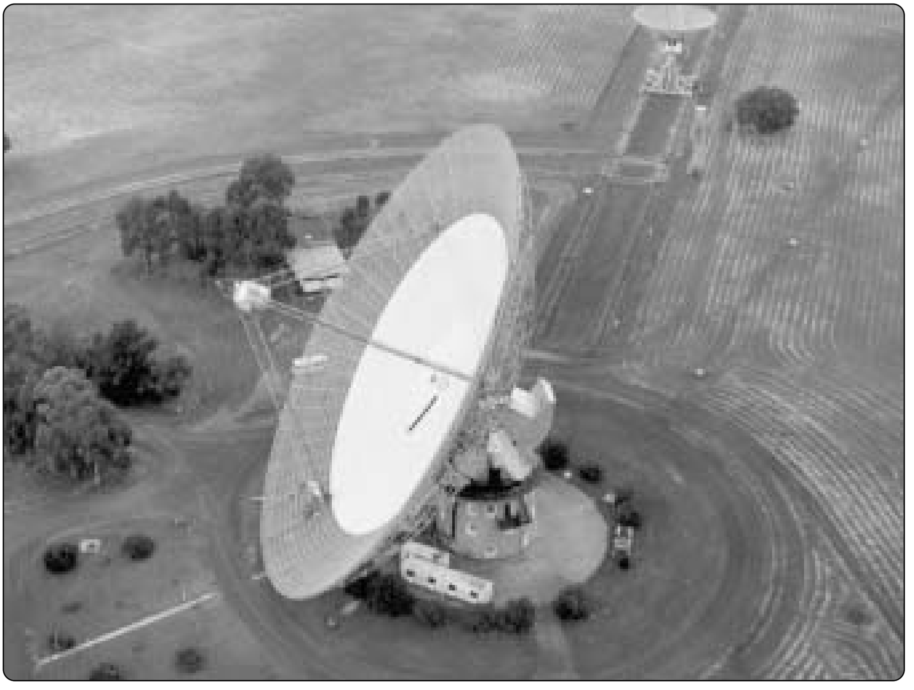

Figure 4-7. Parkes 64-m radio astronomy antenna.

The downlink performance of all the DSN arrayed complexes and the enhancement that would be provided by the addition of the Parkes antenna to the CDSCC array is shown in Figure 4-8, which is taken from this study.

In addressing the specific needs of Voyager at Uranus, the study had started with the Voyager project requirement for an imaging science data return of 330 full frame images per day, with about 30 to 50 images per day in the few months preceding encounter. Coupled with this requirement was a possible improvement in the efficiency of the spacecraft telemetry data transmission system resulting from the use of new coding and data compression techniques in the spacecraft Flight Data Systems. The new spacecraft capability would be implemented by inflight reprogramming of the two redundant Flight Data System processors to function as a dual parallel data processor. This enabled the spacecraft to transmit the science telemetry at lower data rates than would otherwise have been possible.

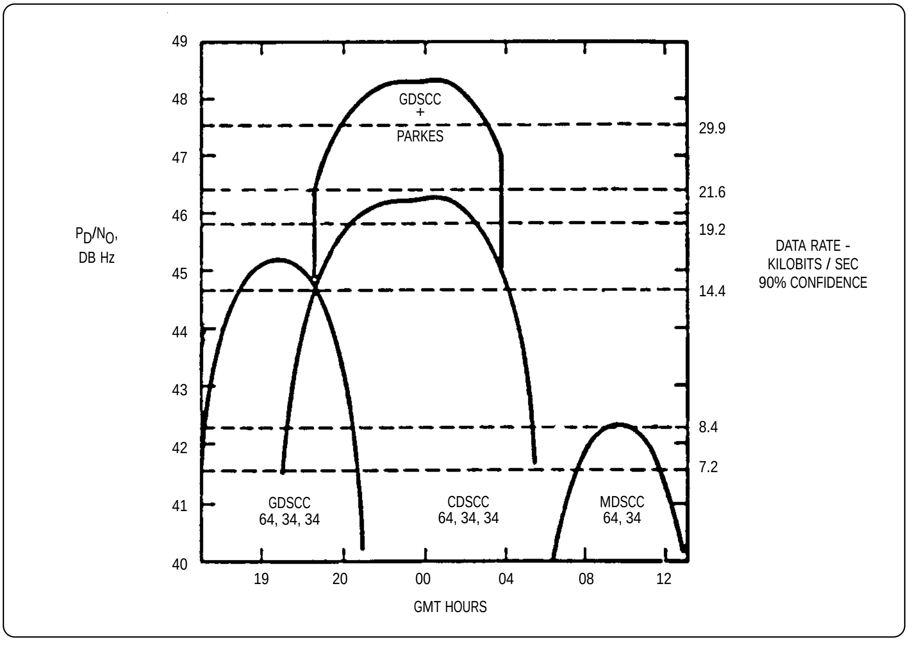

Figure 4-8. Enhanced link performance for *Voyager 2* at Uranus. The figure predicts how the telemetry data downlink between the Voyager spacecraft at Uranus and the DSN antennas on Earth would vary as Earth rotated. The vertical scales depict the maximum sustainable rates at which science data could be transmitted over the downlink (right) with their equivalent signal-to-noise ratios (left). The rotation of Earth is represented on the horizontal scale in terms of GMT. The lower curves represent the situation for arrayed antennas at each of the DSN sites in Goldstone, California; Canberra, Australia; and Madrid, Spain. The upper-center curve shows the greatly enhanced performance that would result from coupling the DSN arrayed antennas at Canberra with the Australian radio astronomy antenna at Parkes.

An assessment of the imaging science data return resulting from this new spacecraft capability and the link performance shown in Figure 4-19 concluded that the combined capability of all three DSN complexes, supplemented at CDSCC with the Parkes Antenna, would be able to return 320 full frame images per day under optimum conditions.

Although there were some qualifications to that estimate relating to spacecraft tape recorder strategy and telecommunications link uncertainties, these were understood and accepted. The requirement was very close to being satisfied in a feasible and cost-effective way, and planning to support Voyager at Uranus with each Complex fully arrayed with one 64-m and two 34-m antennas (only one 34-m at Madrid) supplemented with the 64-m antenna at Parkes, went forward.

This would be the first time that interagency support had been provided for a major planetary encounter, and as such the Parkes-Canberra Telemetry Array (PCTA) would be a "pathfinder" for further applications of this technology. And much sooner than was foreseen at the time, interagency arraying would become established as an alternate resource for DSN support of many NASA and non-NASA deep space missions.

It would be a busy time for Director Tom Reid and his staff engineers as implementation of the PCTA and preparations for the Voyager Uranus Encounter played out simultaneously at the Canberra Complex. Nevertheless, it was a situation Reid had experienced on several occasions in the past. In fact, most of the major expansion of the tracking facilities at the Canberra Deep Space Communication Complex (CDSCC), in Tidbinbilla near Canberra, took place during Tom Reid's directorship of the Complex. In that eighteen-year period, the 64-m antenna was built and later increased in size to 70 m; the 26-m antenna was enhanced to 34 m; a new, high-efficiency, 34-m antenna was built; and X-band uplinks and downlinks were added. Their successful integration into the Network and subsequent record of outstanding service to NASA spaceflight programs owed much to his cooperation.

A native of Scotland and an electrical engineering graduate of the University of Glasgow, Reid served in both the Royal Navy and the Australian Navy before taking charge of telemetry services for the Australian Weapons Research Establishment's rocket test range at Woomera in 1957. His association with NASA began in 1963 with radar support for the Gemini program, at the Red Lake site near Woomera. In 1964 he took charge of the NASA tracking station at Orroral Valley, moved to Honeysuckle Creek in 1967, and in 1970 he was appointed to succeed R. A. Leslie as Director of the Tidbinbilla Station.

His crisp management style and penchant for clear lines of authority, particularly in his relations with JPL and NASA personnel, made a visit to "his" Complex a memorable experience for many Americans. He ran the station in a disciplined, formally organized way that attracted and retained the best technical staff available. As a direct result of their teamwork and his leadership, the CDSCC played a critical role in all of NASA deep space missions in the years 1970 to 1988.

At the time of his retirement in 1988, his wife, Margaret, represented the Australian Capital Territory as a senator in the Australian Parliament.

The design and operational use of the arraying system would be based on the successful demonstration of arraying techniques in a DSN operational environment that had been observed during the Jupiter and Saturn encounters, and the additional new DSN capabilities that were becoming available as part of the Mark IVA implementation effort.

Unlike the DSN antennas, which were colocated at each Complex, the Parkes antenna was some 280 kilometers CDSCC. In addition, it required completely new receiving and telemetry equipment to make it compatible with the Voyager downlink. The design and implementation of the PCTA was a joint effort of JPL, CSIRO, and the European Space Agency (ESA).[24] ESA became involved because of an existing arrangement with CSIRO to support an ESA mission to Comet Halley called Giotto, in 1987, shortly after the Voyager Uranus Encounter.

In summary, CSIRO was to provide a new feedhorn and antenna with upgraded surface for X-band operation, ESA was to provide the X-band maser and down converter, and JPL was to provide an interfacing microwave assembly, 300-MHz receiver, formatting and recording equipment and a baseband data interface to the 280-km intersite microwave link supplied by the Australian Department of Science.

Together, these facilities provided the critical elements of a real-time combining system similar to that used at Goldstone for the Saturn Encounter with DSS 14 and DSS 12. However, in this case a special, long-baseline, baseband combiner would be required at CDSCC to compensate for the much longer delay on the baseband signal path between Parkes and CDSCC. At CDSCC, baseband signals from DSS 14, DSS 42, and DSS 45 would be combined first, before being combined with the Parkes baseband signal in the long-baseline combiner. In addition, the new Mark IVA monitor and control facilities provided greatly improved conditions for correctly operating these very complex configurations in a critical real-time environment. A functional block diagram of the Parkes-CDSCC telemetry array configuration is shown in Figure 4-9.

Because of the critical role of CDSCC and Parkes in the Uranus Encounter strategy, both sites were provided with pairs of Mark IVA digital recorders to back-up the real-time system with baseband recordings, at both sites.

Arrangements at the Goldstone and Madrid complexes were similar, but simpler. At Goldstone, the baseband signals from DSS 14 and the two 34-m antennas, DSS 12 and DSS 15, were combined in the new Mark IVA Baseband Assembly (BBA) which, in addition to the baseband combining function, carried out the functions of subcarrier demodulation and symbol synchronization. These two latter functions had been carried

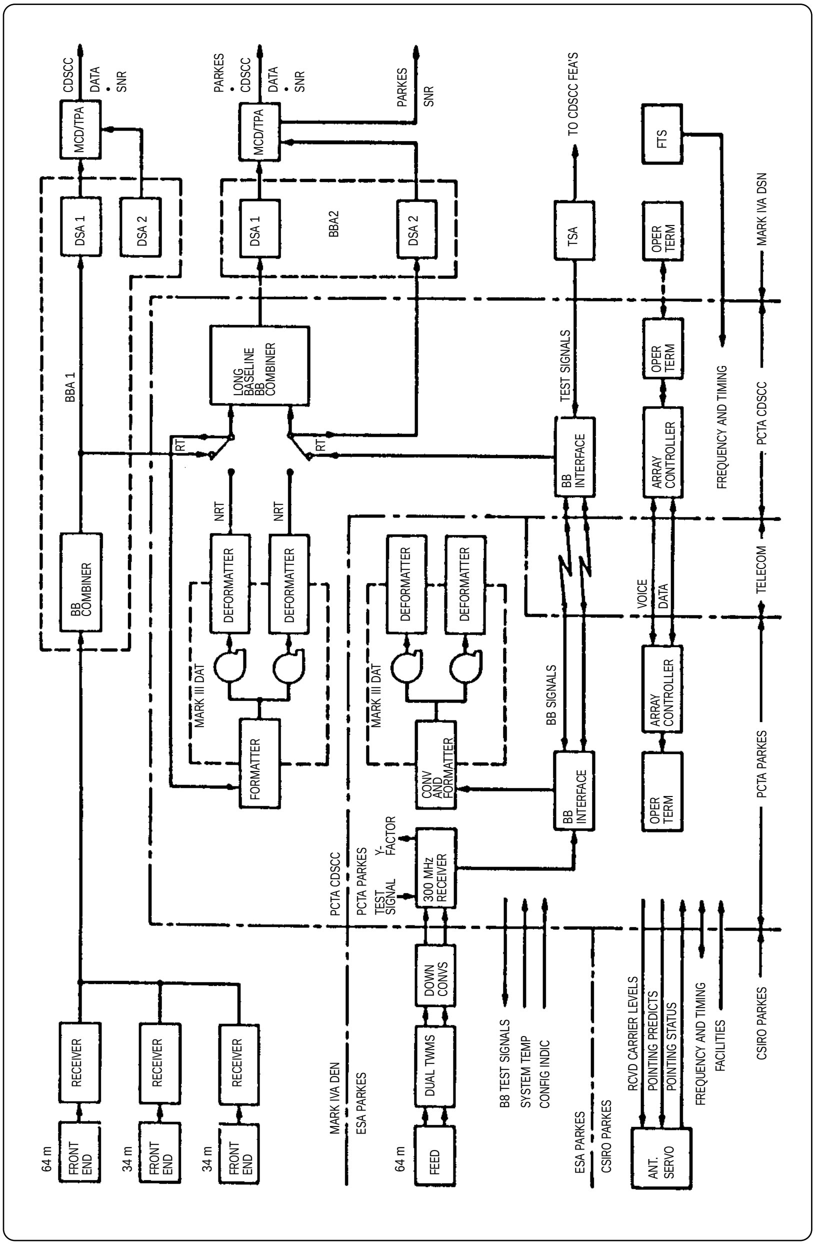

Figure 4-9. Functional block diagram of the Parkes-CDSCC telemetry array for Voyager Uranus Encounter, January 1986.

out by separate assemblies in the former Mark III system. At Madrid the array consisted of just the 64-m antenna and the 34-m standard antenna at DSS 61.

In addition to its downlink capability, a further item of great concern in connection with the Uranus Encounter was the pointing capability of the DSN antennas.[25] To avoid degrading the downlink signal from the spacecraft significantly, it was determined that the DSN antennas must be pointed to less than 0.16 of the antenna half-power beamwidth. This corresponded to less than six one-thousandths (6/1,000) of a degree or 6 millidegrees (mdeg) for the 64-m antennas, and 11 millidegrees for the 34-m antennas. The new Mark IVA antenna pointing system contained new computers and new equipment, all of which required new calibrations and procedures for making the calibrations.

There were two ways of pointing the DSN antennas. In "blind pointing," an antenna pointing prediction program derived from the spacecraft ephemeris, the antenna computers are fed data for necessary corrections before sending pointing signals to the servos to drive the antenna. This method did not rely on any downlink signal from the spacecraft, and was used during radio astronomy occultation observations and spacecraft acquisitions. In "conical scanning" (conscan) the antenna was moved in a conical scanning motion about the approximate direction of the spacecraft. Error signals, derived from a comparison of the downlink signal strength at opposite parts of the scan pattern, were used to drive the antenna to a "null" position. The "conscan" mode thus enabled the antenna to sense the apparent direction of the spacecraft radio signal. This method was useful in the absence of accurate predictions, or for searching for a "lost spacecraft" signal.

During the pre-encounter period, a process for initial pointing calibration of the Mark IVA antenna system was developed at the Madrid Deep Space Communications Complex (MDSCC), using radio stars as distant target points of known position. After a series of radio star observations, the data were reduced to pointing angle offsets and used to produce a systematic pointing error model. These data then provided the corrections needed by the antenna predicts program for "blind pointing." Typical accuracies obtained from these observations were less than 4 mdeg for the 64-m antennas and less than 6 mdeg for the 34-m antennas.

However, radio stars near the 23-degree south declination of the *Voyager 2* spacecraft were not available. For that declination, "conscan" offset data from live Voyager tracking passes were used. Comparison of the apparent direction of the spacecraft signal given by conscan, with the direction given by the corrected predict program, was the conscan offset. To the extent that the conscan properly sensed the apparent direction of the spacecraft signal, the conscan offsets determined the total system pointing errors. Using this method on a large number of tracks at Goldstone, it was determined that the conscan defined axis and the actual antenna beam axis were coincident within 1 to 2 millidegrees. Subsequent tests at Goldstone verified that the downlink signal level was not significantly affected by the method used to point the receiving antenna. With this basic information in hand, the CDSCC carried out an extensive program of blind pointing exercises in preparation for support of the radio science events connected with the Uranus encounter.

These investigations substantially improved DSN confidence in the ability of its antennas to support the outer planet missions without incurring significant downlink degradation due to pointing errors, and laid to rest the initial concerns about antenna pointing errors relative to the imminent Voyager Uranus Encounter.

The regular weekly Voyager project meetings provided a forum for discussion and resolution of the issues and concerns described above. Based on these discussions, Voyager and DSN representatives gradually developed a mutually acceptable plan for DSN support of what was by then called the Voyager Uranus Interstellar Mission.[26] Marvin R. Traxler continued to represent the DSN in these negotiations, while the project was represented by George P. Textor, the newly appointed Mission Director for the Voyager project.

The DSN plan for Uranus met the project requirements for downlink telemetry at a maximum data rate of 29.9 kilobits per second, improved the quality of radiometric data for spacecraft navigation purposes, and further improved and expanded the radio science data gathering capability of the Network. Antenna arraying techniques, based on past experience with the Jupiter and Saturn encounters, and including the new, 34-meter high efficiency antennas and the Parkes radio astronomy antenna in Australia, were used to enhance the downlink signal power received by the DSN stations, while the Mark IVA-1985 model of the Network provided the new capabilities required to provide telemetry, command, radiometric, and radio science services for *Voyager 2* at the Uranus encounter.

Both of these initiatives represented major increments in Network capability and were subsequently used to great advantage not only by *Voyager 1* and *2*, but by all of the other ongoing missions. The engineering and implementation particulars of these concurrent streams of activity and the sensitive task of bringing them into service to meet the Voyager need date (mid-1985), without disruption to the routine operational support of the ongoing missions, are discussed later this chapter.

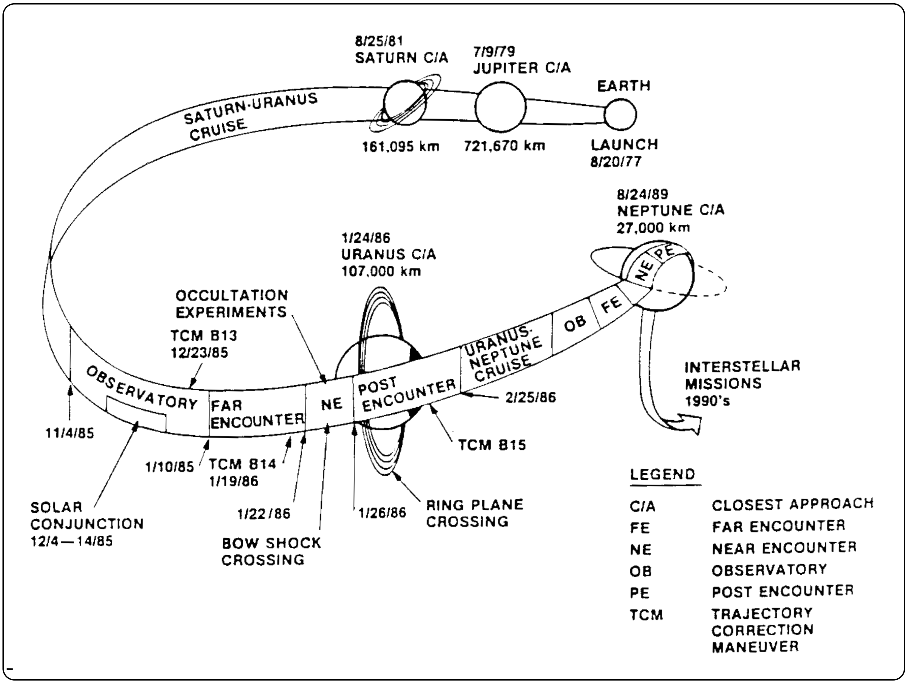

Figure 4-10. Pictorial diagram of *Voyager 2* mission.

Uranus Encounter

On 4 November 1986, 81 days before *Voyager 2* was due to flash by the outer planet Uranus, the Voyager flight team began continuous, extended observations of the Uranian system at better resolution than possible from Earth. The one-ton spacecraft was then travelling at nearly 15 km per second (relative to Uranus), and radio signals travelling at the speed of light were taking 2 hours and 25 minutes to reach the DSN antennas on Earth, 2.88 billion km away. Uranus lay 103 million km ahead. This was the start of the observatory phase during which the spacecraft and DSN would be fine-tuned to prepare for the close encounter observations. A pictorial diagram of the *Voyager 2* mission including all its planetary encounters is given in Figure 4-10.

Two weeks earlier, the Voyager Flight Team had conducted a Near Encounter Test (NET) to validate the readiness of all elements of the project, including the DSN Flight Team and Science Team, to commence the Uranus Encounter operations depicted in Figure

4-22. DSN participation in the NET demonstrated that while the DSN had the basic capability to support the Near- Encounter phase, additional operational proficiency would be needed to reach the level deemed appropriate for those critical operations. This was in large part attributable to the schedule slips that had occurred in the Mark IVA implementation project. Hampered by budget changes and software problems, completion of the implementation tasks had consumed the time that was originally planned for operational training and proficiency activity.

On 5 November 1986, the DSN reviewed its status and responded to the deficiencies that had shown up in the NET. Arraying, radio science, and operator training were the principal areas of concern. The review found that, with the help of specialist engineering personnel supplementing the station operations crews during critical periods, the DSN was ready to support the observatory phase. Further, the observatory phase would provide sufficient additional operational experience to enable the stations to deal with the Far- and Near-Encounter phases. With this proviso and several hardware and software liens against various elements of the new Mark IVA system, the DSN prepared to meet what was possibly its greatest challenge yet, the *Voyager 2* encounter of Uranus.

The spacecraft made its closest approach to the planet on 24 January 1986. Despite the earlier anxiety about its scan platform, onboard computers, and one remaining active radio receiver, the Voyager spacecraft performed perfectly. A final trajectory correction maneuver scheduled for 19 January was canceled since the flight path was deemed satisfactory without further refinement. After travelling an arc of nearly 5 billion km to Uranus, the Navigation Team estimated that the spacecraft passed within 20 km of the aim point. This astonishing navigational accuracy had been achieved by the use of spacecraft optical navigation to complement the Doppler, ranging and Delta differential one-way ranging (DDOR) data types provided by the DSN. Navigation accuracy is critical to the success of crucial science observations that depend not only on knowledge of the spacecraft position but also on proper, accurate pointing of the instruments aboard the steerable scan platform. The spacecraft executed these complex sequences without incident. The science data return quickly grew to avalanche proportions as each of the science instruments carried out its preprogrammed observations. Previously unknown facts about the planet, its atmosphere, rings, magnetosphere, winds, and satellites were soon being presented to the "happily bewildered" scientists. Typical of the many beautiful imaging science results is the striking picture of Miranda, one of the inner moons of Uranus, shown in Figure 4-11.

Figure 4-11. *Voyager 2* image of the Uranus satellite Miranda.

At a distance from Earth of two billion km (1.212 billion mi) and traveling at 65,000 km (40,000 mi) per hour, *Voyager 2* passed within 31,000 km (19,000 mi) of Miranda's surface. Image motion compensation prevented smearing of the image during the long exposure times necessitated by the low lighting conditions at Uranus. The clarity of this image amply demonstrates the capability of the Voyager imaging system combined with the benefits of image motion compensation and the excellent performance of the DSN downlink communications channel.

The new Mark IVA systems all worked well throughout the encounter period. At all sites, array performance, including the Parkes element at Canberra, was close to predicted values. The complex and lengthy radio science sequences at CDSCC were executed without significant loss of data. The new Mark IVA Monitor and Control System created some difficulty at first, while the operations crews adjusted to the concepts of centralized control in a critical operational environment.

For the DSN, the Voyager Uranus Encounter in January 1986 had been a challenge in deep space communications and operations complexity. To meet the Voyager requirements for science data return, the DSN had designed, implemented, and put into operation a complex system of arraying all the DSN antennas at each longitude. At Canberra, the array had been supplemented with a non-DSN 64-m antenna, 280-km distance, belonging to a foreign agency. On the project side, a risky but successful inflight reprogramming of onboard computers had increased the efficiency of the telemetry data stream to complement the DSN improvements in the downlink performance. Special uplink tuning sequences were required to compensate for the Voyager spacecraft receiver problem.

At the same time, the DSN had completed a Network-wide upgrade of the entire data system to increase its overall capabilities and decrease operations costs by introducing centralized control to station operations.

Together, the new technology, new methodology and limited time, created a difficult position for the DSN in the weeks prior to encounter. Responding to this situation, DSN operations and engineering personnel in Pasadena, Goldstone, Canberra, and Madrid were able to meet the challenge and the science returned from the Voyager Uranus Encounter attests to their success.

In the Voyager Uranus Encounter, three major advances in DSN capability, represented by the Mark IVA Data System, antenna arraying, and centralized operations control, had been successfully demonstrated under the most critical operational conditions. These capabilities would carry the DSN forward into the Galileo Era, where once again the Voyager mission would stretch the DSN downlink capability to its limits—the next time at Neptune.